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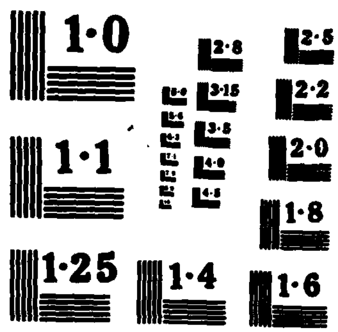
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Semiannual Report

1 October 1984 to 31 March 1985

"Switchable Zero Order Diffraction Gratings as Light Valves"

Office of Naval Research

Contract N00014-84-K-0073

Submitted by

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May 15, 1985

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Background

This project aims to produce a light valve based on the principle of the cancellation of the zero order of diffraction. The light valve works by the displacement of two facing aligned phase gratings with respect to one another by half of a grating period. The light valve is to be simple and mass producible into matrix addressable arrays. Such arrays would serve as displays or as spatial light modulators in optical signal processing.

The material we have chosen to fabricate such valves is polyvinilydine fluoride (PVF_2). It is transparent to visible light and is also strongly piezoelectric. The piezoelectricity would be exploited to produce the motion. On the basis of our previous research we have chosen to fabricate the gratings by embossing and to produce the motion using a chevron geometry which amplifies the motion created by the piezoelelctricity.

In earlier work on this contract we have developed techniques for successfully embossing gratings of 3.8 μm period 0.25 to 1.5 μm deep into PVF_2. The fabrication of templates for this embossing was also developed. In addition, a chevron pattern scheme has been developed to produce motion from the piezoelectricity of the PVF_2. The motion has been observed but has not been combined with light switching.

Progress in the Half-Year

a) Embossing

Using the optimum temperature and pressure a dozen gratings were embossed to be used in the final fabrication of a light valve. Most were about 1 cm in size and had large areas of good quality, so that the 1 mm areas required for the light valves are easily available.

A theory is being developed to understand the triangular slip planes which are always observed under the indented part of the deeper square wave gratings in PVF_2. Deformation and slip theory is being adapted for this purpose.

b) Fabrication of Light Valve

Using the techniques of photolithography and reactive ion etching described in previous reports a number of chevron structures have been fabricated on the films of PVF_2 in which gratings had been embossed. Microgluing and microcrimping techniques have been developed to attach the chevrons and the movable grating to the stationary grating. The actual fabrication of the light valve is in progress.

A paper was presented at the SPIE meeting on displays in Los Angeles, CA., in January 1985. It will be published in the proceedings of the conference (copy attached).

720-19

A Display Based on Switchable Zero Order Diffraction Grating Light Valves

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Abstract

A flat panel display technology has been conceived which utilizes a matrix of line addressable light valves back lighted with a partially collimated source. The basic pixel element of the display is an optical switch based on the zero order of diffraction by two aligned transmission phase gratings. The transmission of light is modulated by mechanically displacing one grating with respect to the other by one-half of the grating period. The color transmitted by the light valve is controlled by the grating profile.

Optical spectra of a large-scale prototype of the switchable light valve element are in good agreement with calculations according to simple diffraction theory. Technology for the construction of an optical switch of the desired size has been developed, with 85% of the area devoted to light transmission. The elements are one millimeter squares made of polyvinylidene fluoride (PVDF), a transparent, piezoelectric plastic. Gratings of nearly square profile with 3.8 micron period are produced in 9 micron films of PVDF by embossing at 4000 bars and 70°C and show the expected optical transmission spectra. Mechanical displacement is produced by applying voltage to two sets of bending arms attached to either side of the movable element. The bending arms amplify motion due to piezoelectric strain. Nickel electrodes are patterned onto the PVDF film by photolithography and liftoff. Perforations around the movable element and the bending arms are etched through the film by reactive ion etching in oxygen, using patterned aluminum as a mask. Motion exceeding 2 microns has been observed, which is sufficient to operate the light valve.

Introduction

A flat display screen to replace the cathode ray tube has been an elusive research and development goal for many years. At present, liquid crystal displays have made significant advances particularly for small dimension system [1]. Electroluminescent, plasma displays, and various other technologies have been pursued [2,3]. A matrix display based on electrostatically activated micromechanical shutters has recently been developed [4].

The goal of this project is to investigate the feasibility of making large area displays (~1 m^2) using a back lighted array of mechanically switched light valves. The concept could lead to a compact, distortion-free video display suitable for applications such as portable microcomputers and computer-aided design. In addition, such an array could serve as a spatial light modulator in optical signal processing.

Our work has concentrated on fabricating a single light valve, which is made of plastic and is in principle suitable for inexpensive mass production into large matrix arrays. In this paper we describe the principle of the light valve and its incorporation into a flat panel display, the fabrication procedures, and present preliminary results.

Zero Order Diffraction

Zero order diffraction of transmission phase gratings utilizes surface relief profiles in transparent material to modulate the phase of an incident optical wavefront. Non-switchable zero order diffraction gratings have been produced by RCA in polyvinyl chloride. With crossed sinusoidal profiles, black-and-white contrast ratios of 200:1 have been achieved [5]. By utilizing color separation and screening techniques commonly associated with color printing, RCA has created color zero order diffraction projection slides with excellent natural color reproduction [6].

The light valve concept is based on a mechanically switchable element in which phase and light transmission are governed by the relative position of two aligned facing gratings. Higher order diffracted light beams are generated according to Equation (1):

$$\sin\theta = m(\lambda)/p; \ m \text{ integer} \tag{1}$$

where θ is the angle from the normal to the plane of the grating and perpendicular to the grating direction, p is the grating period and λ is wavelength. The higher orders of diffracted light are intercepted inside the display, and only the zero order reaches the

viewer.

Optical transmission spectra for arbitrary grating profiles can be calculated according to simple diffraction theory when the Kirchhoff approximation applies, for p>>λ [6,7]. The phase of the emerging wavefront is determined by the amplitude of the grating h, the grating profile, and the index of refraction of the material n. Consider the case of a square profile grating with 1:1 line-to-space ratio. For a particular wavelength and grating amplitude, any odd multiple of a π phase shift will result in complete destructive interference of the wavefront in the zero order. With a white light source, the zero order diffraction grating functions as a subtractive color filter. The optical transmittance t is:

$$t(\lambda) = \cos^2 \left(\frac{\pi(n-1)h}{2}\right) \tag{2}$$

The switchable light valve is constructed with two facing gratings, a bigrate, which can be switched as shown in Figure 1. In the first case (a), the gratings are positioned such that zero order diffraction results in complete destructive interference of a selected wavelength and the transmission of the corresponding desired color. When the gratings are displaced by one-half period, as in case (b), the optical path length through any section of the grating is equivalent, there is no relative phase shift, and all spectral components are fully transmitted. Switching the light valve requires controlling the relative position of the two gratings to produce a displacement of one-half grating period. The two positions switch the light valve pixel element from color to white [8].

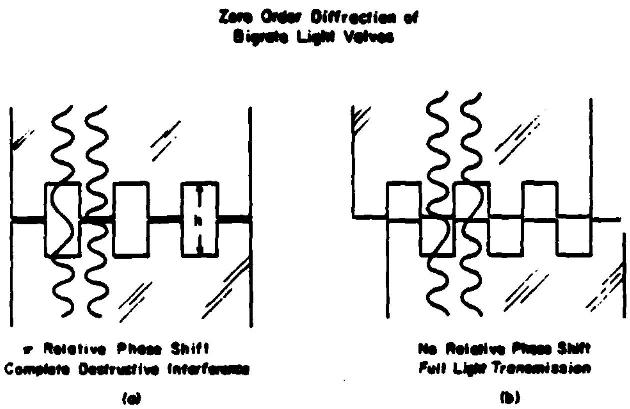

Figure 1. Zero order diffraction principle of the optical switch.

Micromechanical Motion

The switchable light valve described in this paper is a one millimeter square pixel element fabricated in polyvinylidene fluoride (PVDF), a transparent, piezoelectric plastic produced by Pennwalt Corp (King of Prussia, PA). This pixel size was selected to demonstrate the feasibility of the zero order diffraction grating light valve concept for alphanumeric display applications.

PVDF can be extruded under a strong electric field to produce a film in which polar polymer chains are aligned. Degradation of its piezoelectric activity occurs at temperatures in excess of 80°C, when viscous relaxation causes the polymer dipole field to become neutralized [9,10]. PVDF exhibits mechanical strain in the direction of extrusion (the machine direction) with applied electric field. For fields below the dielectric breakdown strength of the material,

$$\varepsilon = d_{31}E \tag{3}$$

where ε is the strain, E is the electric field in volts/meter, and d_{31} is the piezoelectric constant, equal to 2×10^{-11} meters/volt. In order to minimize the voltage required for switching, 9 micron PVDF film is used. For the proposed display application, the piezoelectric constant is insufficient to produce the required motion in the bigrate light valve without amplification.

Motion amplification for switching the light valve element is produced by a planar chevron configuration of bending arms adjacent to and affixed to the transmission diffraction grating. The chevron element is shown schematically in Figure 2. Applied voltage produces piezoelectric strain in the machine direction of the PVDF. The bending arms convert this strain to amplified lateral motion of the grating.

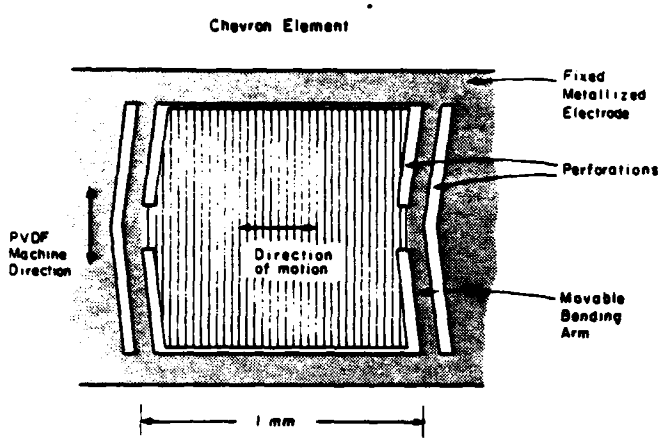

Figure 2. Micromechanical light valve element.

With 200 volts applied to bending arms 20 μm wide and with an angle of 175° between them, a force of 3.2×10^{-6} N is exerted on the movable part of the light valve. The corresponding acceleration results in a displacement of 1 μm in 100 μsec. This is approximately the amount of time available to switch a pixel if it were operated at TV picture rates.

Light Valve Matrix Display

The switchable zero order diffraction grating light valves require light source collimation of ±10° perpendicular to the grating axis, but no collimation is needed along the grating axis. The light source for the flat panel display can be constructed with simple reflective optics such as flashlight bulbs and reflectors.

Removal of higher order diffracted light is done by intercepting these beams with black baffles. A schematic of the light valve pixel element as it would be included in the display is shown in Figure 3. The baffles must be long enough to intercept the limiting ray of the first order diffracted beams, a thickness of less than a centimeter. The baffles are covered by a protective ground glass screen, which diffuses the zero order light to make the display viewable over large angles.

The display concept involves a matrix of these light valve which are line addressable, and can be incorporated into a flat panel display. By mechanically immobilizing all but one row of light valves while simultaneously applying switching voltages to the columns, the display is line addressable and includes pixel storage. The braking mechanism can be electrostatic. A transparent strip of PVDF with a transparent electrode is laid over the chevron element. The lower stationary grating also has a transparent electrode, so that voltage applied to the transparent electrodes will produce electrostatic clamping. If the separation of the electrodes is 30 μm, then 30 volts provides sufficient clamping force to prevent the chevron element from moving when a signal is applied to the bending arms.

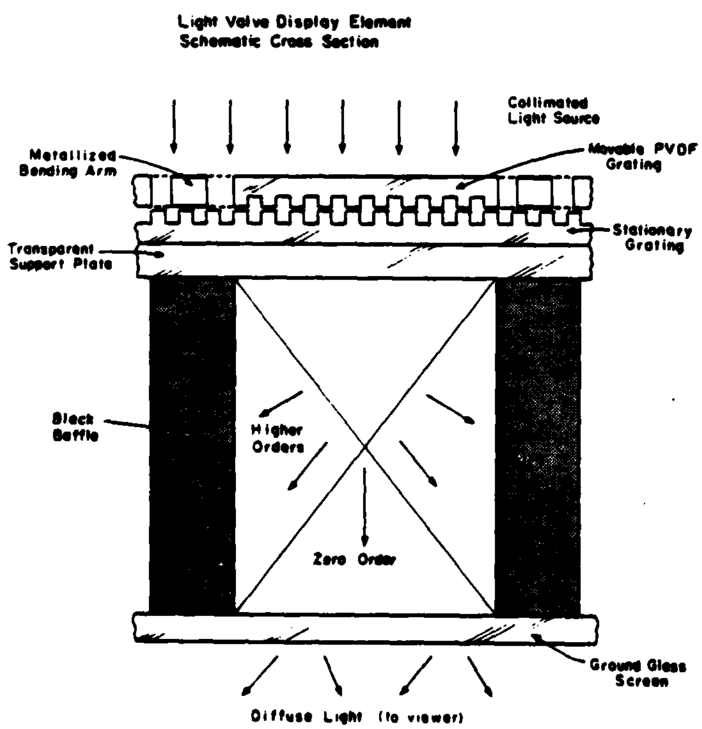

Figure 3. Schematic cross section of a pixel element of the flat panel display.

Light Valve Fabrication

In an early experiment, a large prototype switchable light valve was constructed with square profile quartz gratings, using unamplified motion from a PVDF strip to operate the switch. The optical transmission of the quartz bigrate is in good agreement with calculated spectra for both positions of the switch.

To make chevron elements of the desired 1 mm pixel size, square profile nickel dies are used to emboss gratings into PVDF. A silicon wafer is coated with Shipley AZ 1470 photoresist to a uniform thickness corresponding to the desired amplitude of the PVDF grating. Ultraviolet contact photolithography is used to transfer a 3.8 micron period grating pattern from a flexible glass photomask. The resulting photoresist grating is coated with 12 nm of sputtered gold to establish a base for nickel electroplating. The chemical composition of the electrolyte and the temperature, pH, and current density are controlled to produce a hard, ductile nickel electrodeposit. Nickel is electroplated to a thickness of at least 50 μm before separation from the silicon wafer. A scanning electron micrograph of the nickel die is shown in Figure 4.

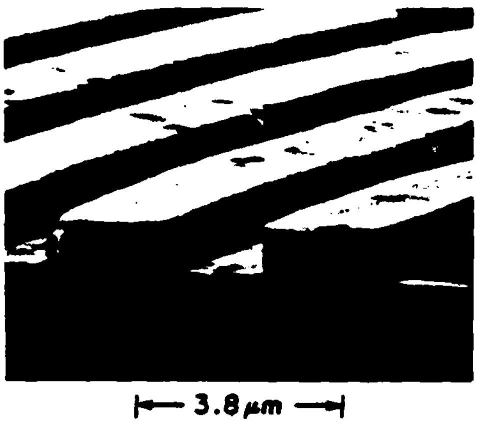

Figure 4. Scanning electron micrograph of nickel die used to emboss PVDF gratings.

Embossing is done in a hydraulic press at 70°C and 4000 bars as shown in Figure 5.

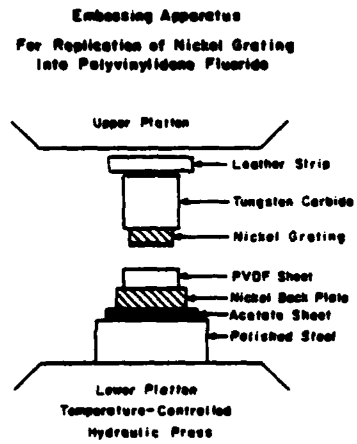

Figure 5. Schematic of embossing apparatus.

PVDF is pressed between a nickel grating, which is aligned along the machine direction, and an optically smooth nickel back plate. A small polished block of tungsten carbide tool steel is used to support the nickel grating, and a strip of leather is used to compensate for aparallelism of the hydraulic press. Embossing pressure is maintained for one minute; the PVDF is removed from the press and allowed to cool to room temperature before separation from the nickel die.

The PVDF grating profile shown in Figure 6 is nearly square. Shear deformation has occurred along slip planes, creating the triangular features in the film below the grating troughs. The zero order transmission spectrum of a PVDF embossed grating is shown in Figure 7 and compared with the theoretical spectrum for a PVDF square profile grating with an amplitude of 1.1 microns. The measured spectrum is consistent with results obtained by RCA for gratings in polyvinyl chloride [7].

Using photolithography and liftoff, nickel electrodes are patterned on both sides of the PVDF film. An embossed grating is first washed in detergent, trichloroethylene, and methanol. The PVDF is mounted on a polished metal support plate using a thin film of vacuum pump oil.

Shipley AZ 1470 photoresist is spun onto the PVDF, and prebaked at 40°C for at least four hours to drive off volatile components. Photolithography is done by intimate contact with a conformable glass mask containing four variations of the basic chevron electrode pattern design, including one which allocates 85% of the display element to light transmission. After development, 80 nm of nickel are deposited by vacuum evaporation, and liftoff is performed with acetone.

The process is repeated on the other side of the film. Photolithography is used once more to pattern a film of aluminum 180 nm thick that will serve as a reactive ion etching

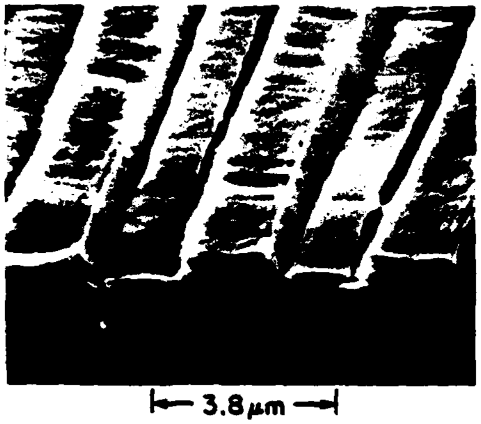

Figure 6. Scanning electron micrograph of PVDF grating embossed at 70°C and 4,000 bars.

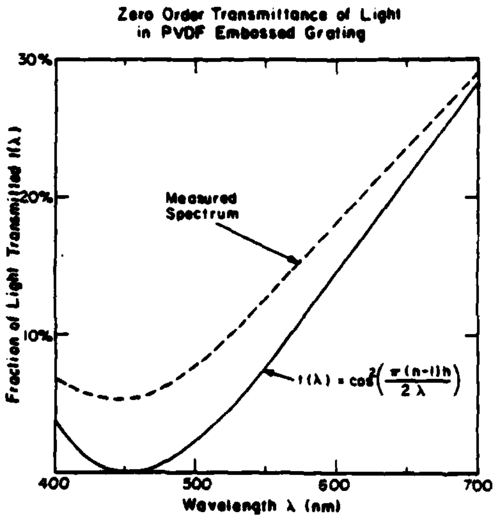

Figure 7. Optical spectrum of a square profile embossed PVDF grating.

mask. The aluminum pattern completely covers the nickel in addition to the central portion of the light valve element, leaving areas to be perforated unmetallized. Figure 8 shows a portion of a chevron element prior to reactive ion etching.

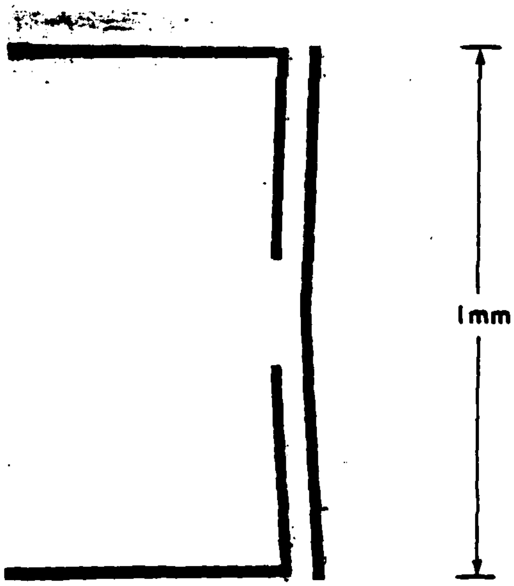

Figure 8. Portion of a chevron element with aluminum reactive ion etching mask.

Reactive ion etching is done using 10 microns of oxygen pressure, 50 watts of power, 1.4 kV peak-to-peak RF voltage, and a DC bias of 475 volts, for at least 150 minutes. The aluminum is chemically removed with dilute sodium hydroxide, leaving the nickel electrodes intact.

Several preliminary chevron elements have been produced which demonstrate the feasibility of switchable light valves. Figure 9 shows a chevron element that was fabricated in PVDF without a grating. This experiment demonstrates the dimensional

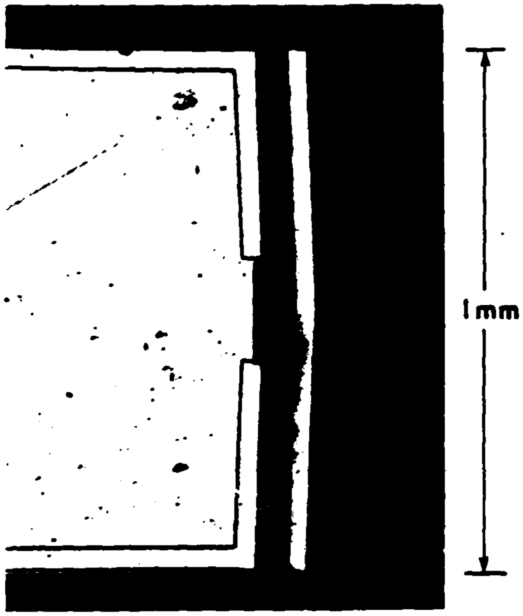

Figure 9. Chevron element in PVDF without grating.

stability of PVDF enabling three stages of photolithography, and the ability to etch perforations and remove excess aluminum while maintaining continuity of the electrodes. Figure 10 shows a chevron element with a grating. The central portion of the chevron appears dark in the photograph due to zero order diffraction. The actual color of the transmitted light is a deep blue.

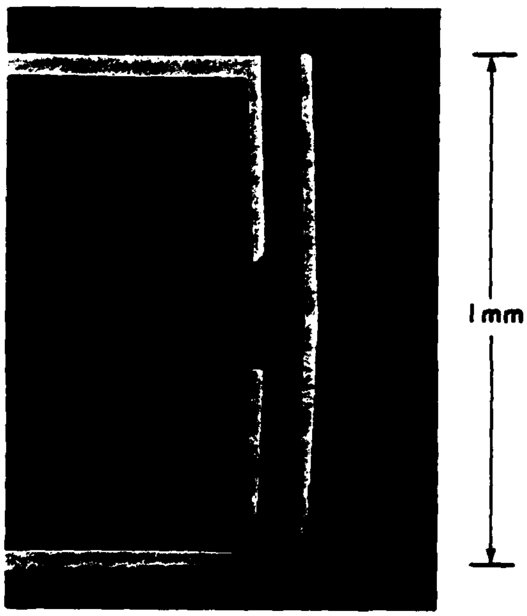

Figure 10. Chevron element in PVDF with grating; dark appearance is due to zero order diffraction.

To demonstrate motion, chevron elements were fabricated which were fully metallized on both sides except for the chevron pattern required for perforation. Figure 11 shows evidence of motion exceeding 2 microns.

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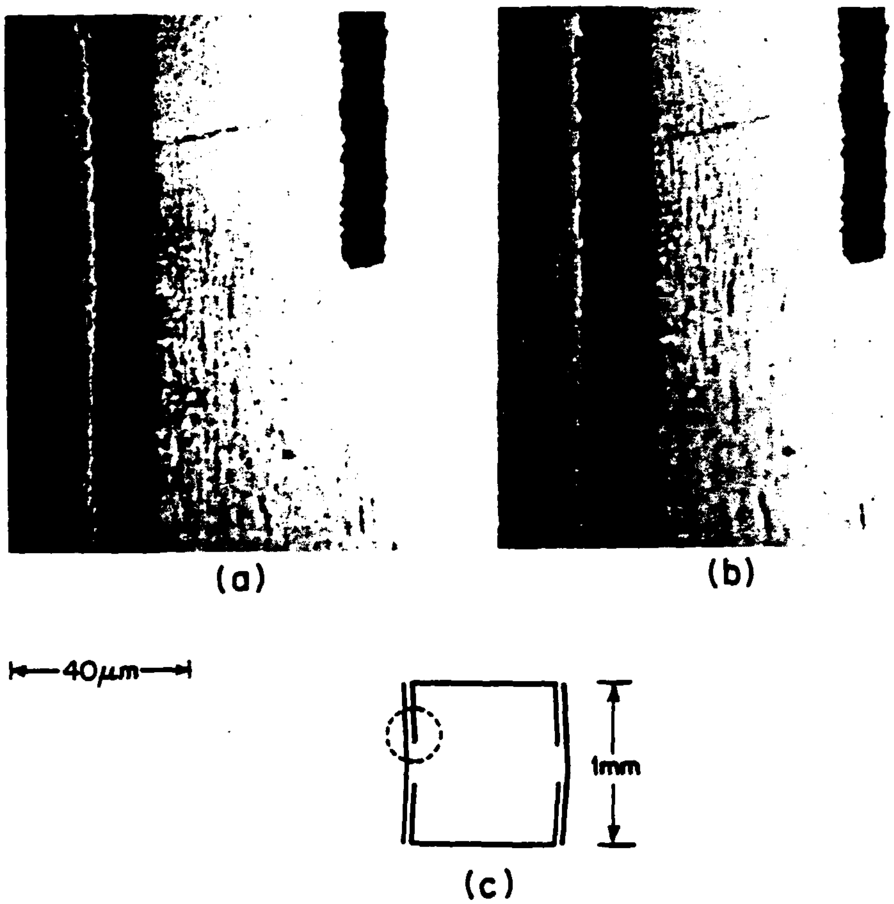

Figure 11. Micromechanical motion produced by piezoelectric PVDF chevron element; (a) and (b) correspond to the portion of a chevron shown schematically in (c). When voltage is applied, the bending arms move the central portion of the chevron element to the right and the gap widens.

Summary

The technology for construction of an optical switch based on the zero order of diffraction has been developed, including the fabrication of gratings in PVDF by embossing, and production of micromechanical motion sufficient to operate the light valve. A large screen flat panel display concept has been presented which utilizes a matrix of switchable zero order diffraction grating light valves.

Acknowledgements

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